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Ground Subsidence and Structural Damage Over an Abandoned Room-and-Pillar Coal Mine at Hegeler, IL

By Gennaro G. Marino, James W. Mahar, Larry R. Powell, and Richard E. Thill

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	mm	millimeter
mi	mile	pct	percent

GROUND SUBSIDENCE AND STRUCTURAL DAMAGE OVER AN ABANDONED ROOM-AND-PILLAR COAL MINE AT HEGELER, IL

By Gennaro G. Marino,[1] James W. Mahar,[1] Larry R. Powell,[2] and Richard E. Thill[3]

ABSTRACT

The Bureau of Mines and the University of Illinois investigated surface characteristics and damage to structures from mine subsidence over a room-and-pillar coal mine in Hegeler, IL. Data on three adjacent subsidence sags and associated structural damage were collected, summarized and evaluated. The subsidence sags developed over a 10-year period and took place above a modified room-and-pillar operation mining the Herrin (No. 6) coal at a depth of 130 to 135 ft. Surface vertical displacements of 3.0 to 3.5 ft resulted from extracting 6.1 to 6.4 ft of coal.

Ground movements associated with sag formation severely damaged three houses and a radio station building, broke numerous utility lines, and structurally distorted three radio transmission towers. The radio station was remodeled and the towers repaired, but the three houses were subsequently demolished. Surface waters collecting in the subsidence depressions caused failure of radial ground transmission systems. The following subsidence profile characteristics were determined at the radio station and one of the houses, respectively: profile slopes, 0.02 and 0.07; maximum curvatures, 2.3×10^{-4} ft^{-1} and 3.0×10^{-4} ft^{-1}; and angular distortions, 6.6×10^{-3} and 62.0×10^{-3}. Although the house was more severely damaged than the radio station, both structures are classified as severely to very severely damaged.

[1]Visiting research engineer, Dept. of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, IL.
[2]Geologist, Twin Cities Research Center, Bureau of Mines, Minneapolis, MN.
[3]Supervisory geophysicist, Twin Cities Research Center.

INTRODUCTION

Mine subsidence and damage to surface structures have been problems in Illinois since the start of extensive underground mining in the late 1800's. The most serious problems are associated with early room-and-pillar practices. Early coal production was obtained from outcrops and shallow seams at depths less than 100 ft (1).[4] The extraction scheme was characterized by irregular layouts and poorly defined areas (2). In older mines, although overall recovery averaged about 50 pct, some panel areas are believed to have recovered as much as 80 pct of the coal (3). By 1975, over 4,000 abandoned underground coal mines were reported in 70 Illinois counties (4). A considerable number of unidentified small mines still exist for which no documentation is known. As of 1975, over 800,000 acres of abandoned underground coal mine workings existed in the State (5).

Subsidence creates topographic changes characterized by tilt, curvature, and displacements of the ground surface (6). Differential movements of the ground surface cause damage to structures and utilities. By 1976, subsidence was reported in 28 municipalities in 18 counties (7). During the first 2 years of operation of the Illinois Mine Subsidence Insurance Program, mine subsidence was found to be the cause and origin of damage to the structures in 20 pct of the files closed. Cost data for repairs are incomplete because about 60 pct of the structures still show active movement. Field data reveal that damage estimates average $20,000 to $30,000 per structure, or total property damage of $1 to $2 million per year (8).

Recently, Illinois mining practices and subsidence characteristics were described (2, 9-11), structural responses to subsidence profile strains were analyzed (12-13), and the Illinois Mine Subsidence Insurance Program was summarized (8).

[4]Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

Two reports on subsidence (14-15) have been prepared as public information for homeowners considering subsidence insurance. In addition, several reports containing data on structural reponses to subsidence at various sites have been published by the Illinois Abandoned Mined Land Reclamation Council.

The nature and extent of damage to surface structures as a result of subsidence movements are not well known in Illinois because there has been very little scientific or engineering documentation of subsidence. To date, few structures have been monitored and little is known about the extent of subsidence effects on the land surface, especially farmland (15). Because no systematic subsidence profile data and accompanying structural damage measurements have been completely synthesized, it is difficult to predict the critical strains, slope, and curvature prevailing at the time of structural damage. Predictions of differential settlements and damage potential of buildings rely on structure-ground surface interactions (16-17). Measurements of differential settlement and horizontal strain on the foundation and adjacent ground are necessary (18-19).

As part of a cooperative mine subsidence research program with the State of Illinois, the Bureau of Mines is measuring the type and severity of subsidence damage and ground profile characteristics to determine the effects of subsidence on surface lands and structures. These data will be used to develop subsidence prevention, control, and repair strategies. First, the mechanics of how a structure is affected by subsidence must be thoroughly understood. Severity of damage with respect to differential settlement and tilt must be assessed to establish a severity index, which must then be verified with respect to the magnitude of ground movements. In addition, valuable information is being collected on what causes room-and-pillar mines to become unstable and collapse causing subsidence.

The development of subsidence prediction methodologies will enable Illinois coal mine operators to comply with regulations for protection of surface land while maximizing resource recovery. By combining the capabilities to precalculate the subsidence profile and the level of damage that may occur to surface lands and structures, coal mine operators will be able to determine the impacts of undermining an area and thus be able to plan an efficient, economic, and safe mine while protecting the surface.

Terminology for subsidence depressions is adopted from Bauer and Hunt (10). In Illinois, pit subsidence is used to describe a depression with nearly vertical to belled-outward walls. Pit subsidence is caused by collapse of shallow, abandoned mines with incompetent overburden. Sag subsidence is expressed by a large depression with gentle slopes. The term "sag" is used to describe the nearly equidimensional subsidence depressions over room-and-pillar mines. The term "trough" is reserved to describe elongate depressions produced over modern longwall and high-extraction room-and-pillar operations. The three depressions that developed on the Hegeler site are subsidence sags, and this term will be used throughout this report.

The purpose of this study is to document and characterize mine subsidence and related damage that occurred over an abandoned room-and-pillar mine between 1967 and 1981. The approach was to collect, summarize, and evaluate the surface ground movements and damge associated with three adjacent subsidence events in Hegeler, IL. The work included collecting news articles, personal accounts, and documents related to the subsidence events; determining the sag configurations; establishing reference points and measuring the existing differential displacements of the ground and structures; and summarizing and evaluating the data. Monitoring of the site is continuing. Future reports will detail the mining and geological conditions relevant to evaluating the mechanisms of mine collapse and changes in overburden properties subsequent to the formation of the subsidence sags.

ACKNOWLEDGMENTS

The results of this report are based on work conducted under Bureau of Mines contract J0205071, initiated under the Minerals Environmental Technology Program. The work was performed by the Civil Engineering Department, University of Illinois at Urbana-Champaign between May 1978 and June 1981.

The authors would like to thank James Jessop, geophysicist, Twin Cities Research Center for support and participation in field activities. The cooperation of Mike Mitzloff, Ralph Cox, and Allan Thomas of the radio station management is acknowledged and greatly appreciated. Robert Bauer and Tony DeVine, geologists with the Illinois State Geological Survey, supplied information about the site. We would also like to thank Paul DuMontelle of the Illinois State Geological Survey for critically reviewing the manuscript and providing protographs and documentation of the early subsidence history at the site.

SITE DESCRIPTION

The study site is located in Hegeler, IL, which is a few miles south of Danville and about 5 mi west of the Illinois-Indiana border (fig. 1). Hegeler can be characterized as a light industrial and agricultural area with a population of about 1,600. The area is extensively underlain by room-and-pillar coal workings that operated between 1870 and 1974.

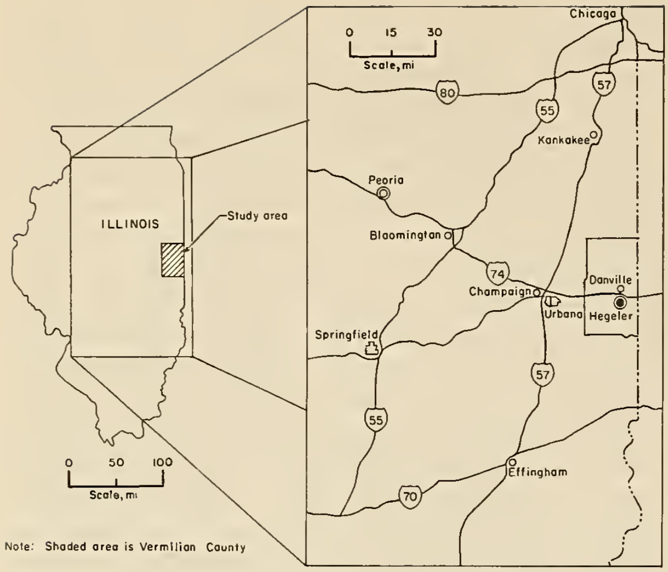

FIGURE 1. - Area location map.

The site is situated in SW 1/4 sec. 29, T.19N, R.11W of the second principal meridian. Subsidence has affected the north side of Spelter Avenue, including a radio station and its three transmitting towers (fig. 2). Farmlands lie to the north and east of the property. The west side of the property is bounded by an embankment probably used in the past for coal hauling. Other properties along Spelter Avenue are residential. The topography is flat to gently rolling.

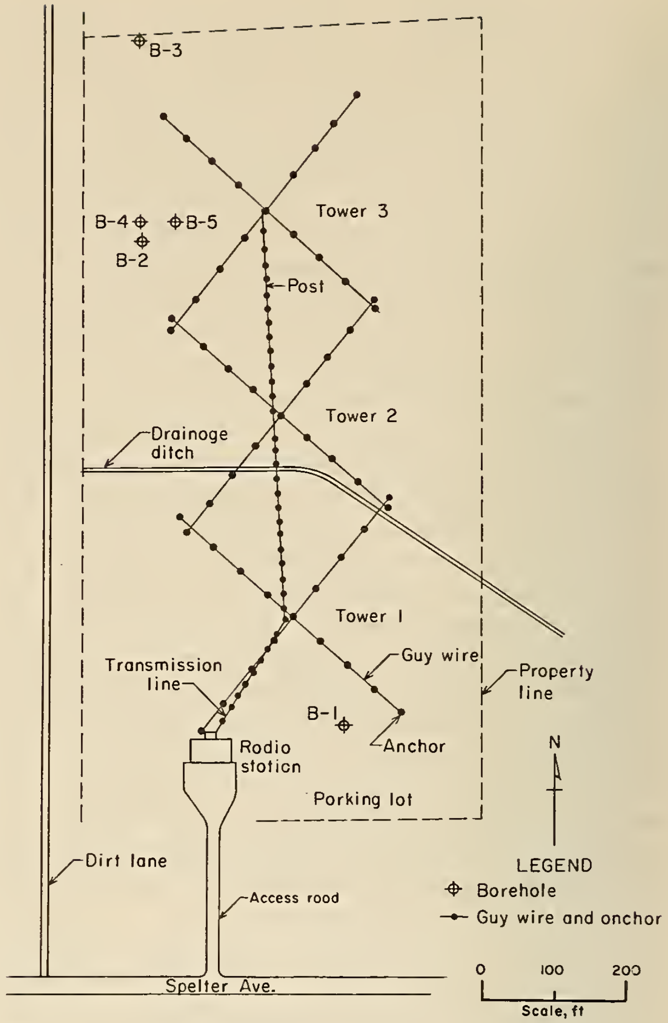

FIGURE 2. - Site location map.

GEOLOGIC CONDITIONS

REGIONAL GEOLOGY

Physiographically, Hegeler lies within the Bloomington Ridged Plain, a region of gently rolling terrain crossed by many glacial recessional moraines that form low hummocky ridges that trend in a general east-west direction. In east central Illinois, the bedrock has been covered serveral times by large continental glaciers during the Pleistocene Series. The surficial deposits include glacial drift deposited during the Wisconsinan, Illinoian, and Pre-Illinoian glacial stages (20). The drift is a complex series of units, including till, which is primarily a heterogeneous mixture of sand, gravel, and pebbles in a compact clay and silt matrix. The thickness of the tills is generally 10 to 20 ft in the study area.

Structurally, the area is situated on the northeastern margin of the Illinois Basin. The basin contains marine and nonmarine Pennsylvanian age sediments that thicken toward southeastern Illinois. The site is located in a broad gentle depression known as the Marshall Syncline, which is bounded on the east by the Cincinnati Arch and on the west by the LaSalle Anticlinal Belt (21). Most of the anticlines and synclines are wide, gentle, and open, and the strata dip 1° or 2°. However, occasional dips of up to 15° are found on more prominent structures (22).

The strata in east central Illinois are essentially flat-lying interbeds of sandstone, shale, coal, underclay, and limestone that were deposited as part of large deltas in a gently subsiding basin (23). The marine, brackish water and delta plain sediments have complex relations making interpretations of their depositional environments difficult. In the Hegeler area, sandstone and limestone are much less abundant than in adjacent areas (24). Frequent and abrupt changes in rock type over relatively short distances are characteristic of coal measure rocks in Illinois.

The rocks immediately underlying the study area are part of the Modesto and Carbondale Formations (fig. 3). The Danville (No. 7) coal is at the top of the Carbondale Formation. It varies in thickness from 2.5 to 5.5 ft and has been mined locally (25). The Farmington Shale is the lowest named unit of the Modesto Formation, located above the Danville (No. 7) coal. It is commonly a gray shale that becomes coarser grained upward. The Carbondale Formation contains the Herrin (No. 6) coal, which is located 120 to 150 ft below the surface in the Hegeler area. It is generally 6 ft thick and overlain by grayish-black shale. Rock units below the Herrin (No. 6) coal consist of an underclay over the nodular Higgensville Limestone followed by a shale and then the Vermilionville Sandstone.

SITE GEOLOGY

The geology beneath the site was determined by drilling five exploratory boreholes to depths ranging from 147 to 159 ft. The locations of these boreholes are shown in figure 2. Split-spoon samples were taken in the glacial till at 5-ft intervals, continuous NX core was obtained in the rock, and thin-walled tube samples were recovered from the underclay. A north-south geologic cross section across the site, developed from the five boreholes, is given in figure 3.

Glacial till, 30 to 47 ft thick, lies directly on the bedrock surface, which forms a gentle bedrock valley centered near the north end of the site. The grain size distribution of the till varies across the site, but no particles greater than medium-size gravel were recovered in the split-spoon samples. Generally, the till consists of two major units. The first unit is a thick layer of dense, coarse-to-fine sand with some clayey silt and medium gravel surrounded by the second unit, which consists of silt and clay. A small lens of dense, coarse-to-fine sand with some fine gravel and silt exists near the bedrock surface at the north end of the site.

The Farmington Shale is present below the glacial tills and is the first bedrock unit encountered in the boreholes. The upper part of the shale, consisting of interbedded shale and siltstone, was encountered only at the south end of the site. Generally, the Farmington Shale is a gray silty shale with both clayey seams and thin siltstone bands that become more frequent toward the base of the unit. In boreholes B-2 and B-5, the lower part of the Farmington Shale above the Danville (No. 7) coal is a thin lens of black carbonaceous shale.

The Danville (No. 7) coal ranges from 4 to 7 ft thick and lies 80 to 88 ft below the surface. It thins and contains more impurities below the black carbonaceous shale. A 6- to 7.5-ft-thick underclay, which grades into a nodular limestone, lies below the coal.

The next unit, the Energy Shale, consists of a sequence of three grayish siltstones, which change from a laminated siltstone at the top to a thinly bedded siltstone with clay layers at the bottom. The unit is 29 to 35 ft thick, and individual facies range from 4 to 23 ft thick.

The Herrin (No. 6) coal is 6 to 7 ft thick at depths of 131 to 135 ft below the surface. The seam has a westerly dip of about 1.2 pct. The underclay is a green-to-gray clayey shale that contains limestone nodules and grades into a discontinous argillaceous limestone. Below the limestone is a 9- to 13-ft-thick gray shale. The lowest rock unit drilled into at the site is the Vermilionville Sandstone. It is a gray-to-green siltstone.

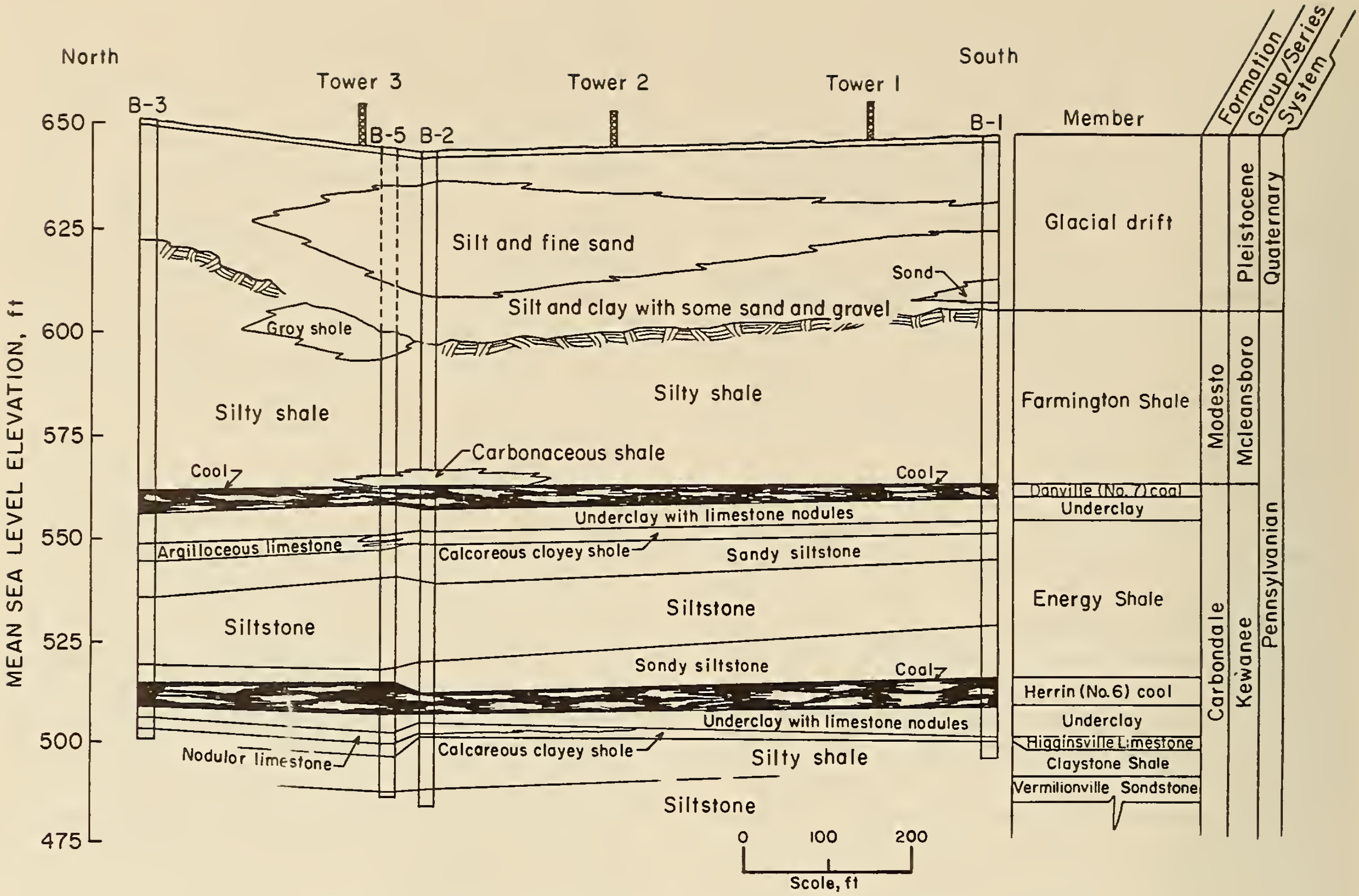

FIGURE 3. - North-south geologic cross section through study site.

The groundwater table generally lies within 10 ft of the ground surface. Based on the borehole data, there are no good soil or bedrock aquifers within 150 ft of the ground surface.

MINING HISTORY AND PRACTICE

The mine that underlies most of the town of Hegeler, and an extensive area north of the site, worked the Herrin (No. 6) coal from 1946 to 1974. The site was undermined from 1960 to 1967. The mine, the last operating deep shaft in the area, was closed in 1974.

The 6- to 7-ft-thick coal seam was mined using a modified room-and-pillar operation (2) with mine openings oriented north-south and east-west (fig. 4). At the project site, working entries were driven westward from the south main. Panels were then developed southward from east-west working mains. A 250-ft wide barrier pillar borders the north edge of the site. After 1953, pillar robbing was not practiced, but as much coal as possible was taken at the working face, contingent upon the stability of the mine opening. The roof of the mine was supported with timber props, and the ratio of timber to mined tonnage was high, which indicates stability problems in the immediate roof.

In the study area, the mine has rectangular pillars ranging in width from 10 to 25 ft, rooms 20 to 45 ft wide, and crosscuts 10 to 25 ft wide (fig. 4). The crosscuts were made about every 85 to 160 ft. The pillar height-to-width ratio ranges from 0.24 to 0.64 and panel width to depth ratios range from 1.9 to 2.8. Under the site, the extraction averages 70 pct with some variation due to different extractions in entries and panels.

SURFACE SUBSIDENCE

SUBSIDENCE HISTORY

Three subsidence sags have developed in the study area between 1967 and 1978. The locations of the sags occurred above areas of high extraction (fig. 4). Subsidence has progressed northward starting with sag 1 in 1967, sag 2 in 1968, and sag 3 between 1976 and 1978. The sags range from 240 to 570 ft in diameter. Sag 1 encompasses the radio station building and an area to the south and west. Sags 2 and 3 developed north of the building in the field containing the transmission towers. Sags 1 and 2 subsided with one main event, but sag 3 developed in two or more major events in which the ground movements have progressed westward. A summary of the subsidence history at the study site can be found in the appendix.

Sag 1 started to develop in the vicinity of the radio station about noon on July 21, 1967. The subsidence eventually encompassed the access road and parking lot and the surrounding area. The ground movements damaged three houses, the radio station, and service utilities to these structures (26-29). In addition, the southern guy wires to tower 1 were tensioned. The maximum settlement (about 3.5 ft) occurred over an area west of the radio station parking lot and access road. Although most of the displacement occurred within 2 days, ground movements were reported as late as October 1967. Then, in May or June 1969, the northern portion of the radio station building sustained additional damage from residual movements in the northern portion of sag 1.

Sag 2 develop in the field north of the radio station building in May or June 1968. The center of the sag is located 40 ft northwest of tower 1. Most of the settlement (3 ft) occurred rapidly within 6 weeks. Tower 1 subsided 2.75 ft, which caused the guy wires supporting the tower to loosen, and they had to be retightened several times. Surface water collected in the sag around tower 1.

In November or December 1976, sag 3 developed under tower 2. The tower nearly failed when it settled and tilted 0.05 ft to the east. In July 1978, residual subsidence of sag 3 produced settlement and lateral movement of the southwest guy wire anchors for tower 3. The upper 150 ft of the tower was bent in response to the ground movements. The maximum settlement was about 3 ft.

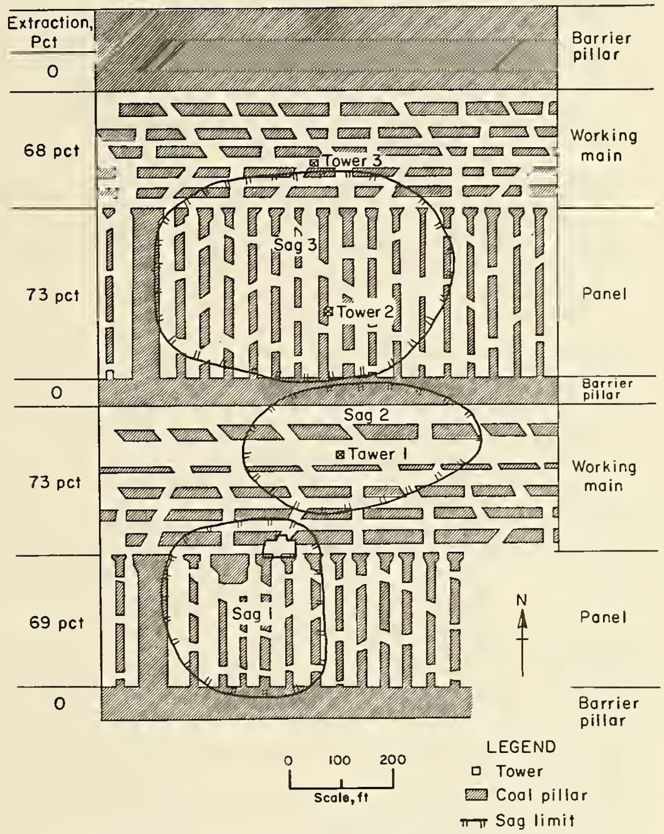

FIGURE 4. - Mine map showing location of subsidence sags.

SAG CHARACTERISTICS

Level surveys were run across each sag to determine apparent maximum vertical ground displacements. Each sag was surveyed at least twice. Horizontal ground movements were also measured periodically using a tape extensometer stretched between posts supporting the transmission line and reference points on the radio station building (fig. 5). Because survey results indicated that no significant horizontal displacement has occurred between late 1978 and 1981, no further discussion will be necessary.

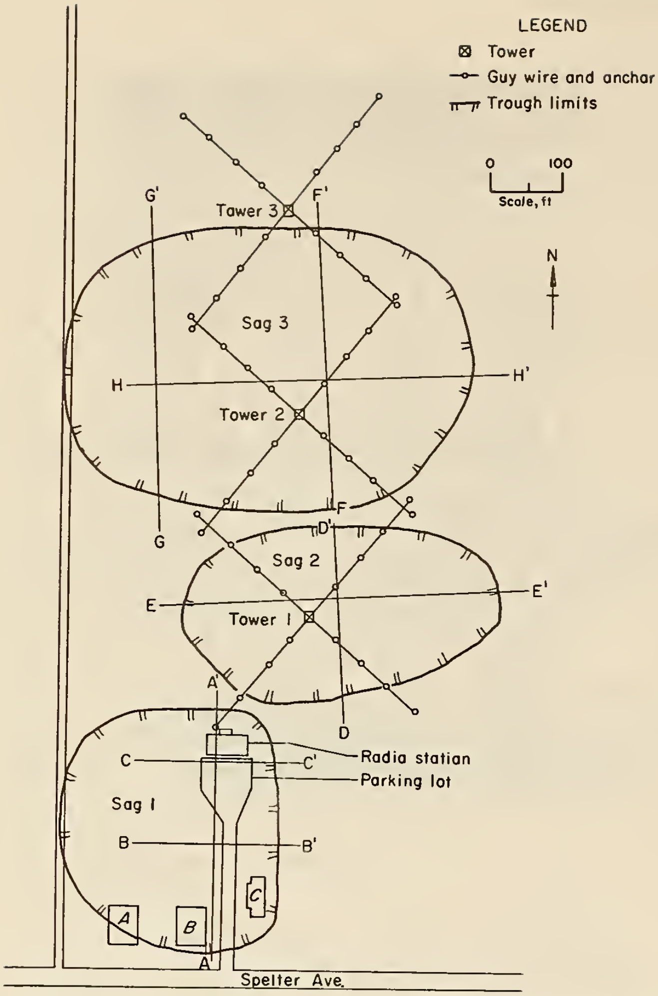

FIGURE 5. - Location of subsidence profiles, cross sections, and reference points.

The limits of subsidence were determined from (1) a map of perimeter tension cracks and compression ridges prepared by the Illinois State Geological Survey (31) in 1967 (fig. 6), (2) accounts of damage from interviews with radio station personnel and owners of the damaged structures in the area, (3) measured differential settlement of the radio station building, and (4) field work by project personnel. Ground surface profiles prior to subsidence were estimated by interpolating linearly across the access road and parking lot to points outside the sag (fig. 7). The profile for sag 1 is located 100 ft east of the center of the sag and was measured after resurfacing of the parking lot.

For sags 2 and 3, profiles were prepared from elevations measured on a 20- to 25-ft grid in order to establish the postsubsidence profiles. The presubsidence profiles were determined by linearly interpolating between the apparent limits of sags and known presubsidence elevations of reference points inside the sags. The following were taken into consideration in drawing the profiles: the drainage ditch as a low point, measurements on the settlement of the tower bases, and estimated limits of the sags as discerned from the postsubsidence elevations.

The adjusted displacement profiles of the sags are presented in figures 8 through 10, and their locations are shown on figure 5. The adjusted vertical displacement is the estimated elevation prior to subsidence minus the respective subsidence profile elevations. The adjusted vertical-displacement profile was determined by drawing a smooth curve through points of known settlement. Slopes and curvatures were calculated based on the adjusted vertical displacement profile and are plotted below the corresponding settlement profiles. Table 1 summarizes sag characteristics.

TABLE 1. - Summary of sag characteristics

Sag No.	1	2	3
Maximum diameter...ft..	350	450	570
Minimum diameter...ft..	310	240	410
Maximum settlement...ft..	3.5	3.0	3.0
Maximum slope...	0.055	0.038	0.034
Maximum curvature, ft^{-1}:			
Compression (+)...	1.2×10^{-3}	8.6×10^{-4}	6.3×10^{-4}
Tension (-)...	1.2×10^{-3}	7.0×10^{-4}	6.4×10^{-4}
Extraction...pct..	66	74	71
Seam height...ft..	6.4	6.4	6.1
Settlement to extraction height ratio...	0.55	0.47	0.50
Mining depth...ft..	130	130	135

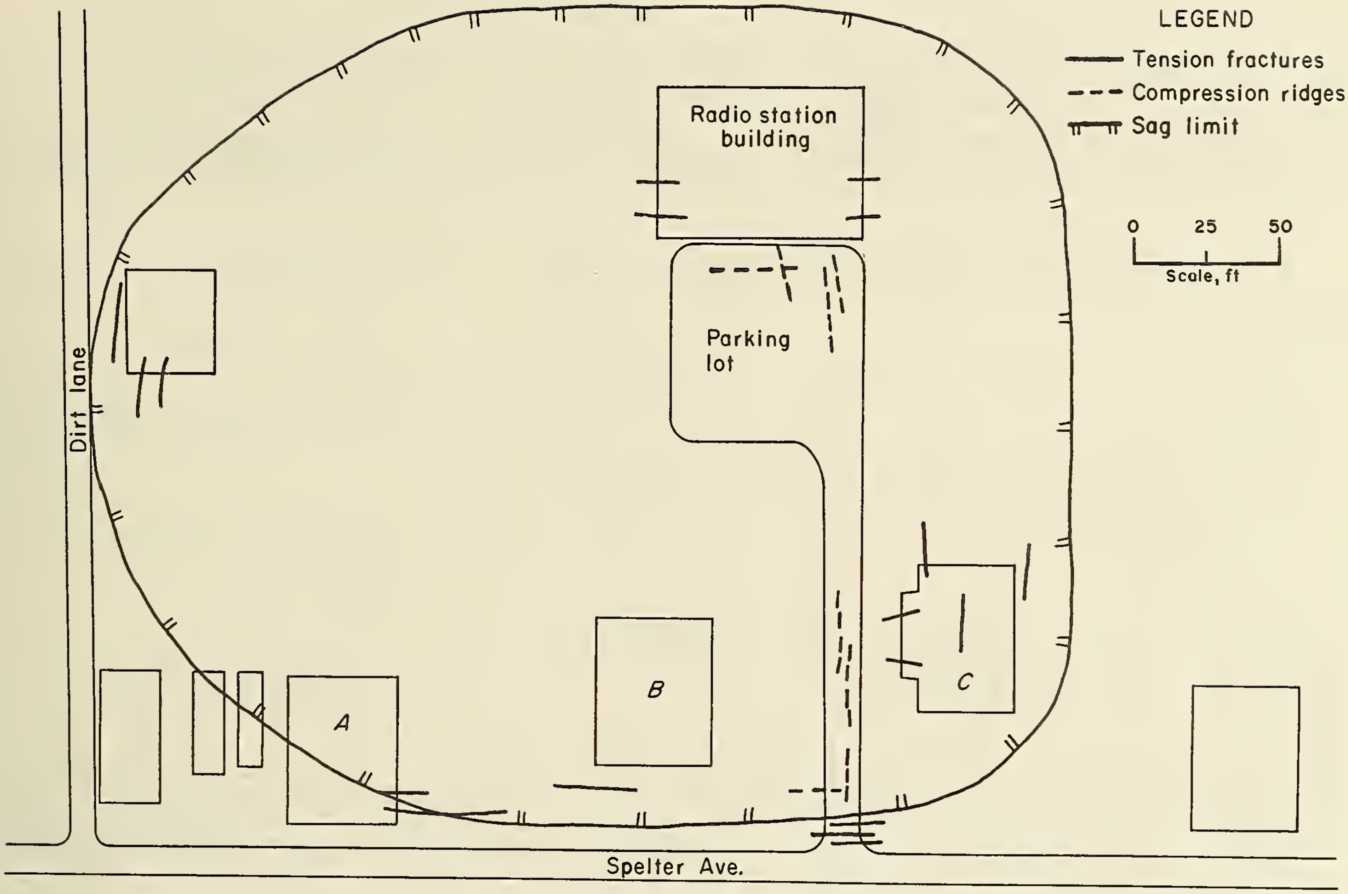

FIGURE 6. - Sketch map of sag 1 tension and compression features in 1967.
(Courtesy of Illinois State Geological Survey.)

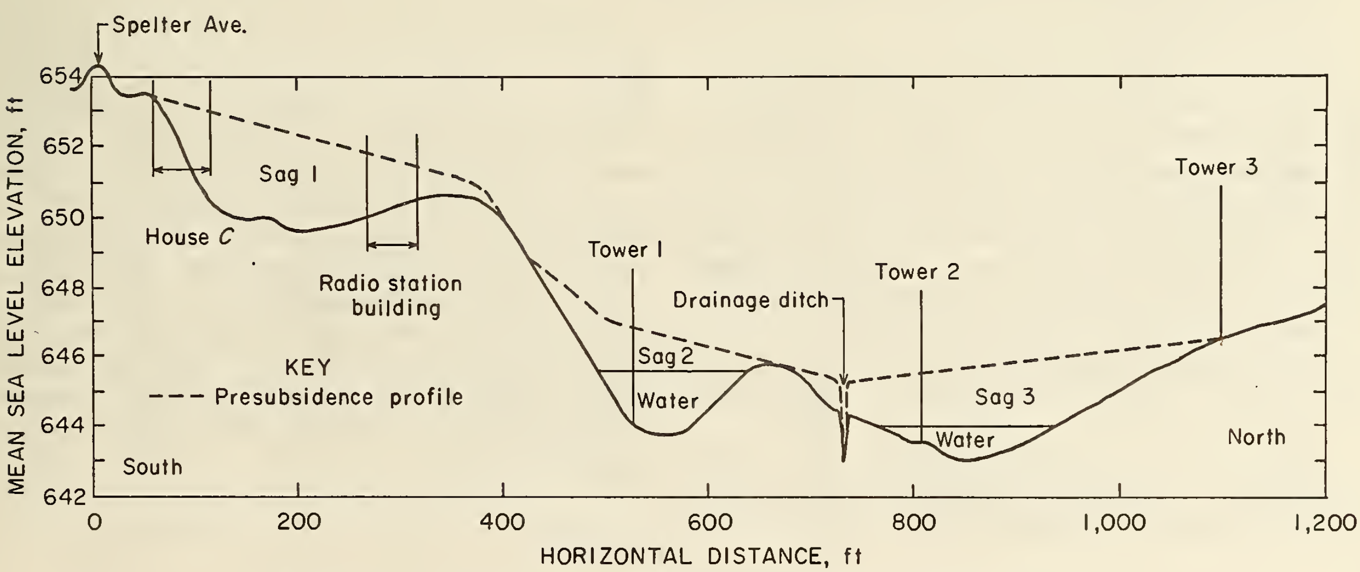

FIGURE 7. - Existing and assumed presubsidence, north-south profile.

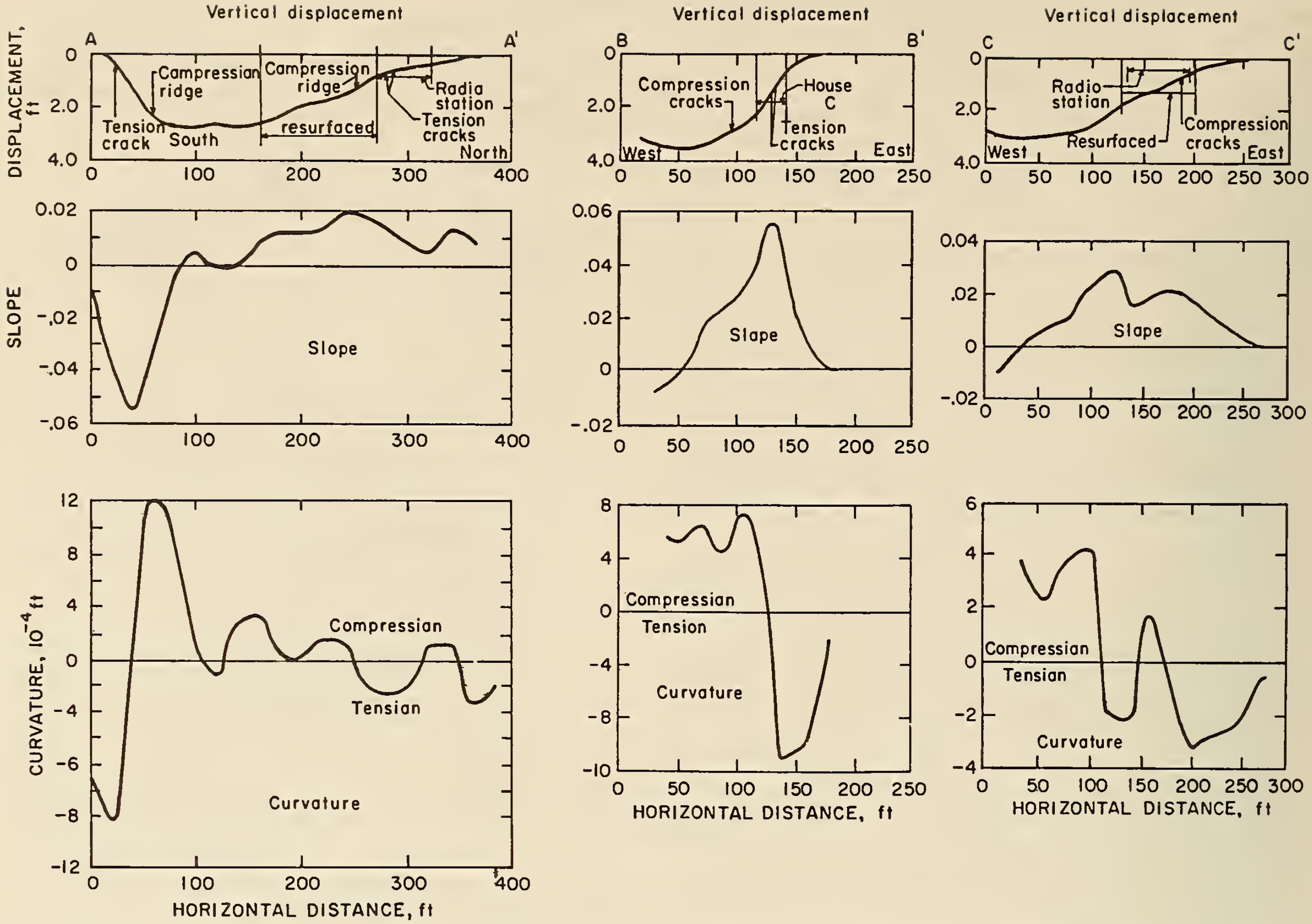

FIGURE 8. - Adjusted profiles, slopes, and curvatures for sag 1. Profile slopes and curvatures calculated on 40-ft lengths from survey data. Surveyed Nov. 11, 1978.

Sag 1 is a 290- by 350-ft semirectangular depression with rounded corners. The area of maximum settlement is approximately concentric to sag limits. A maximum settlement of 3.5 ft is located 100 ft west of profile A-A' (fig. 8). The ratio of settlement to extraction height, known as the subsidence factor, is 0.55.

The maximum slope[5] in sag 1 is 0.055 and occurs on the southeast side where house C was located (fig. 8, B-B'). Slopes decrease to the north. Around the radio station building, the maximum slope is roughly 0.02. Both structures are located in the tension zone but on opposite sides of the sag. Curvatures, corresponding to the maximum tension and compression, are 1.2×10^{-3} ft^{-1} on the south side of the sag and 2.0 to 4.0×10^{-4} ft^{-1} on the north side. Figure 11 shows tension cracks and compression ridges associated with sag 1.

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[5]Slope is a ratio between any like units of length or distance (feet to feet, inches to inches, etc.).

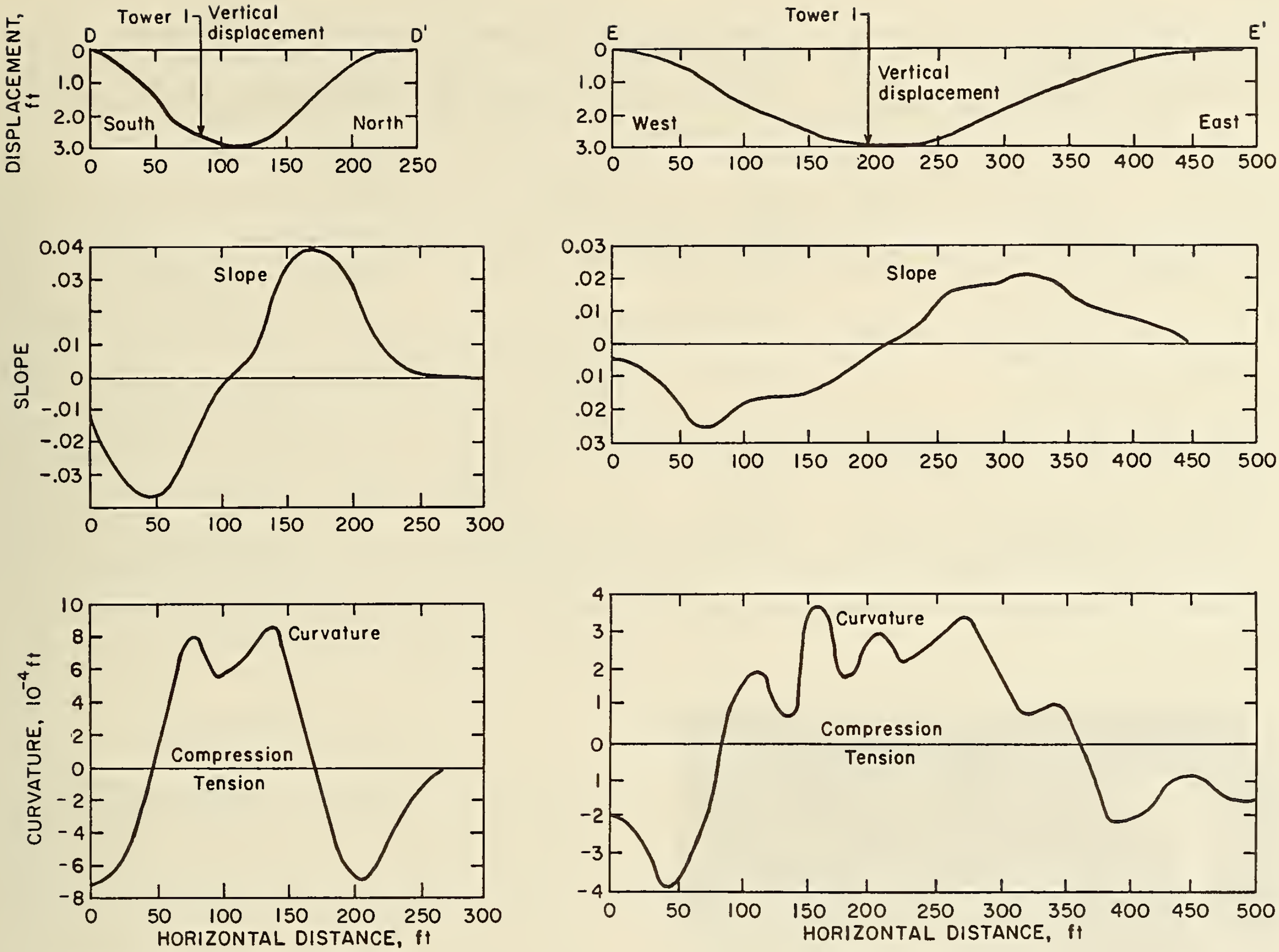

FIGURE 9. - Adjusted profiles, slopes, and curvatures for sag 2. Profile slopes and curvatures calculated on 40-ft lengths from survey data. Surveyed July 9, 1981.

Sag 2 is a 450- by 240-ft elliptical depression elongated in the east-west direction. The sag encompasses the base of tower 1 and most of its guy wire anchors. The adjusted displacement profiles (fig. 9) show the sag to be a bowl-shaped depression with a maximum settlement of about 3 ft.

Slopes for sag 2 are greatest along the north-south profile (fig. 9, D-D') where the maximum slope is 0.038. This value is 1.5 times greater than the maximum slope in the east-west direction. The maximum curvatures are 8.6×10^{-4} ft^{-1} in the compression zone and 7.0×10^{-4} ft^{-1} in the tension zone. Both occur along the north-south profile and are about twice those in the east and west portions of the sag.

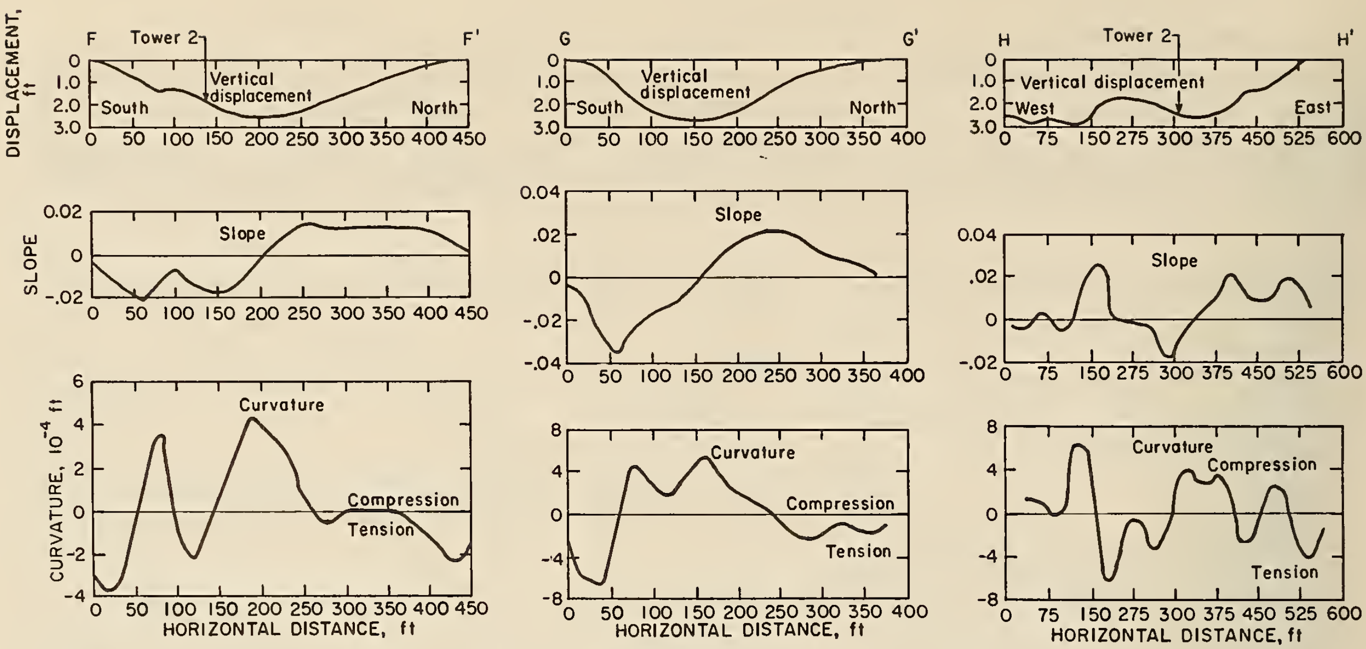

FIGURE 10. - Adjusted profiles, slopes, and curvatures for sag 3. Profile slopes and curvatures calculated on 40-ft lengths from survey data. Surveyed July 9, 1981.

FIGURE 11. - Photographs of 0.33-ft-wide tension cracks (*A*) and 0.25-ft-high compression ridges (*B*) from sag 1 on June 24, 1967. *(Courtesy of Illinois State Geological Survey.)*

Sag 3 is oval with a maximum east-west diameter of 570 ft and a minimum north-south diameter of 411 ft. The sag encompasses nearly all of tower 2 and the southern guy wire anchors of tower 3. Figure 10 shows that in the north-south direction, the sag has a uniform smooth profile (F-F' and G-G'), but in the east-west direction, the sag bottom varies by 1 ft or more (fig. 10, H-H'). The maximum settlement is 3.0 ft.

The maximum slope for sag 3 is 0.034, which occurs on the south side of profile G-G' (fig. 10); however, slopes greater than 0.02 exist in many other areas of the sag. Curvatures in the compression and tension zones are 6.0×10^{-4} ft^{-1} and occur in the western part of the sag, but in the eastern part they are as great as 4.0×10^{-4} ft^{-1}. Both slopes and curvatures are erratic in the east-west direction and reflect the nonuniform settlement profile across the bottom of the sag.

SAG INTERRELATIONSHIPS

The three sags developed above the same mine and in similar geologic conditions. Sags 1 and 3 are above working panels, have semirectangular shapes, and are bounded on the north by working entries, and on the south and west by barrier pillars (fig. 4). They have displacement profiles with relatively flat centers and nearly equal curvatures in the tension and compression zones. On the other hand, sag 2 occurred over a working entry bounded by a barrier pillar on the north and wide pillars on the south. It has a distinct bowl-shaped profile with the maximum compressive curvature greater than the maximum tensile curvature. Sag 3 is the largest, but probably consists of two overlapping sags or an initial small sag that progressively enlarged. Sag 2 is the smallest and has its long axis parallel to the underlying working entry.

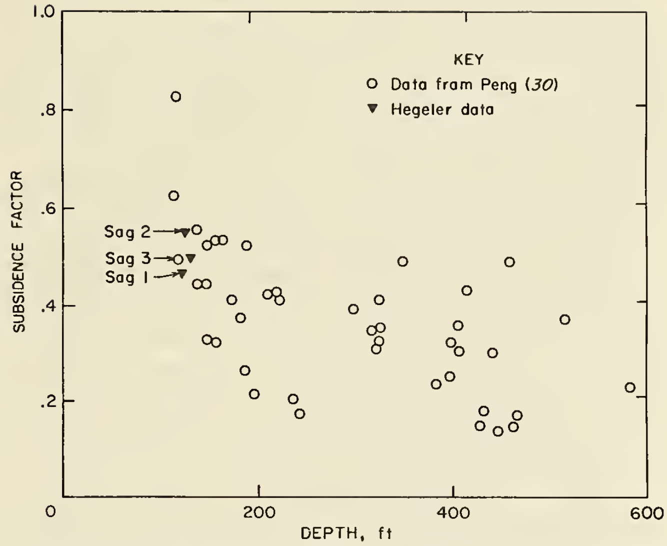

FIGURE 12. - Relationship between mine depth and the subsidence factor.

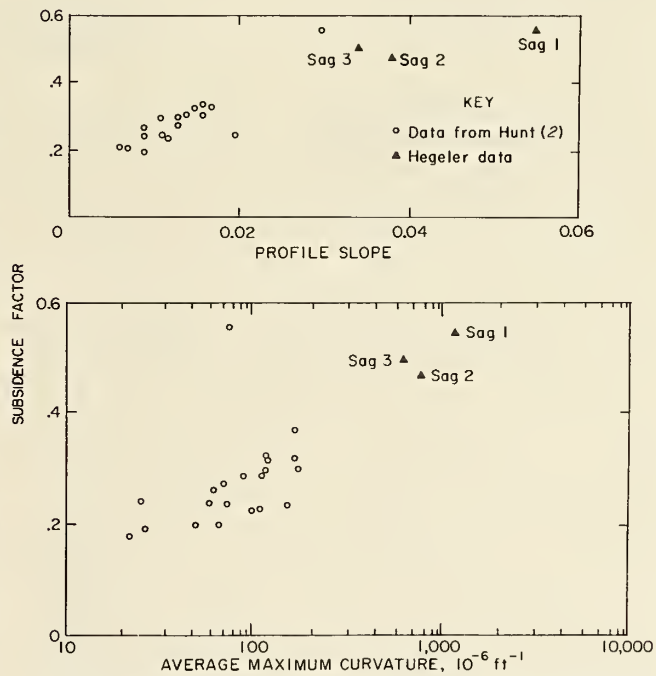

FIGURE 13. - Relationship between the subsidence factor and (*A*) profile slope and (*B*) average maximum curvature.

In figure 12, the subsidence factor is plotted against mine depth for subsidence cases over Illinois room-and-pillar mines. The Hegeler subsidence sags are comparable with other subsidence sags at similar mining depths in Illinois. The general trend of the plot shows decreasing subsidence with increasing depth.

In general, the maximum slopes and curvatures of subsidence sags tend to increase with increasing subsidence factors. These relationships are shown by Hunt (2) for subsidence profiles in Illinois. The sags at the Hegeler site, however, are more severe than those studied by Hunt (fig. 13).

Figure 14 shows that maximum tension and compression are almost equal in cases of Illinois mine subsidence above abandoned room-and-pillar mines. However, when compared with data from other Illinois mines, the Hegeler sags are much more severe.

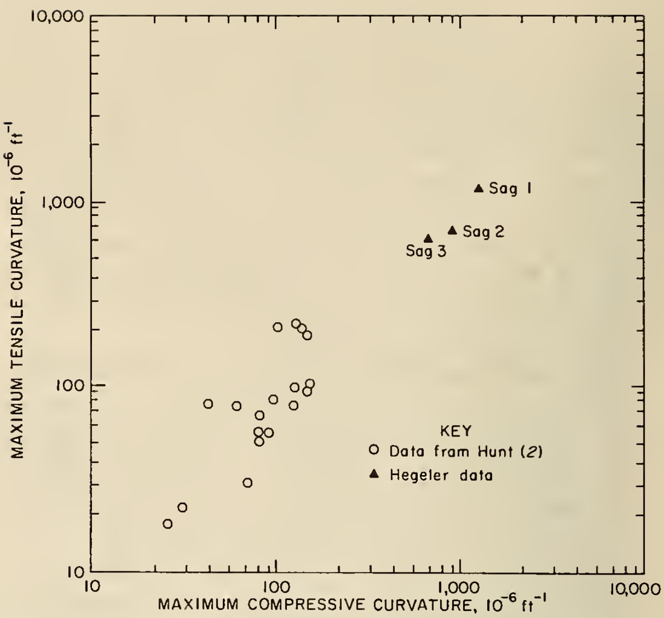

FIGURE 14. - Relationship between maximum tensile curvature and compressive curvature.

STRUCTURAL DAMAGE

Damage caused by the three sags occurred before initiation of the study. Data on damage associated with sag 1 are based on newspaper accounts, personal interviews, an Illinois State Geological Survey report (31), and observation of the structures. Damage information related to sags 2 and 3 were obtained from radio station personnel and observations.

Newspaper accounts (26-29) on sag 1 reported that gas and water lines were broken and telephone lines were pulled away from the houses. Houses were described as "leaning" toward the center of the sag. Foundations were cracked and window and door frames were distorted. The radio station floor and walls were cracked, windows and doors were distorted, and the rear of the building was separated from the foundation.

Two houses (A and B) affected by sag 1 were abandoned and removed before 1975. A third house (C) was removed in 1978 after damage observations were recorded. The locations of these houses are shown in figure 5. The radio station was inspected after it was remodeled. The behavior of house C and the radio station due to subsidence is described in the following sections. Houses A and B are not discussed because of insufficient data. Behavior of the radio towers in response to subsidence is presented, followed by a comparison of structural damage to the nature of the subsidence profiles.

BEHAVIOR OF HOUSE C

Subsidence damage to this structure was described and recorded during May 1978. It was a two-story structure with a partial basement and crawl space (fig. 15). The superstructure was wood-framed with interior walls made of plaster on wood lathe and supported on bearing walls two-bricks thick. No attachment was found between the bearing walls and the superstructure. The foundation consisted of three-brick thick wall footings.

The house was located in the tension zone just inside the southeast corner of sag 1 (fig. 6). Vertical-displacement contours related to sag 1 are shown in figure 16. The ground movements subjected the house to large horizontal strains, angular distortions, rigid body tilt, and translation. Profile B-B' in figure 8

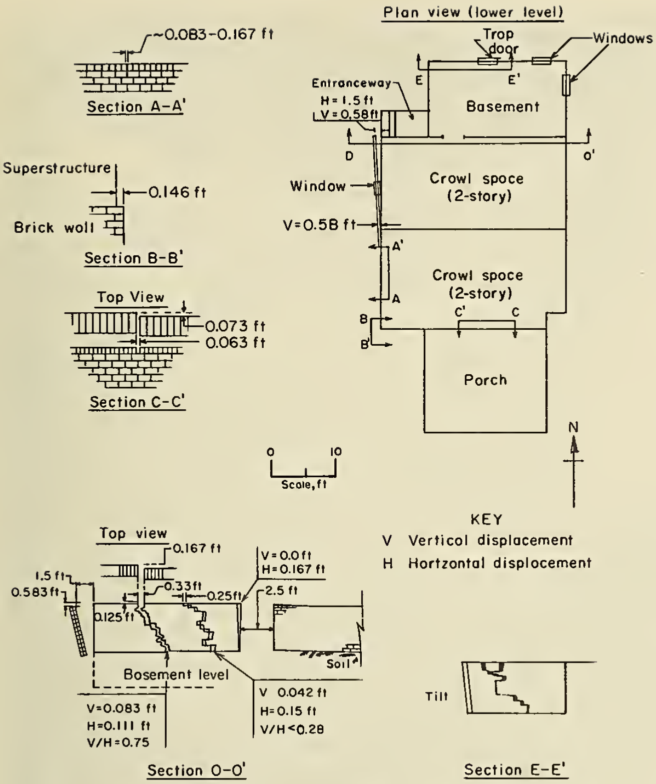

FIGURE 15. - Plan of damage to house C. The damage was measured in May 1978. (Sections shown are not to scale.)

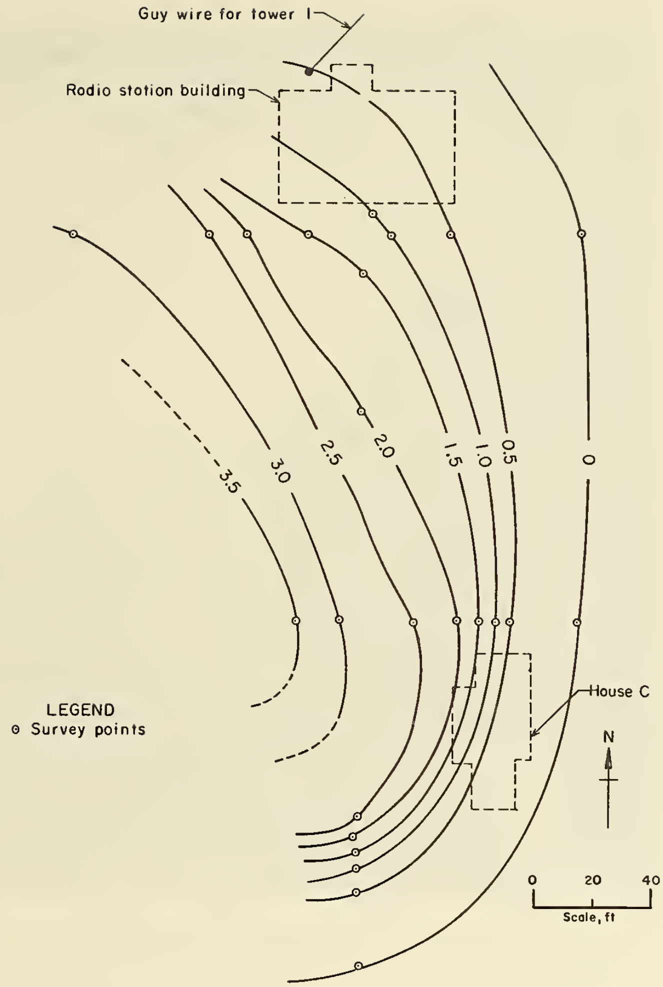

FIGURE 16. - Vertical-displacement contours for sag 1. Survey performed in November 1978.

shows that the maximum slope and curvature of the sag in an east-west direction occurred within the length of the house. The differential settlement across the structure was 0.75 ft from north to south and 1.0 to 1.5 ft from east to west.

The bearing walls and on-grade members cracked, separated, and tilted in response to the ground movements. Cracks opened as much as 0.33 ft, and walls separated as much as 1.5 ft. The west brick wall of the crawl space tilted, settled, and moved laterally away from the superstructure (fig. 15, sec. D-D'). At the north end, it separated horizontally 1.5 ft and vertically 0.58 ft from the interior bearing wall. These wall displacements occurred because there was no foundation-superstructure attachment between the exterior and interior walls. The vertical separation prevented the development of frictional resistance between the sill and wall, thus there was essentially no restraint against outward movement. Most of the damage to the west wall was caused by differential rigid body tilt.

The relationship between profile slope and wall tilt is illustrated by the wall separations and crack widths in the northwest corner of the basement (fig. 15, sec. E-E'). Here crack widths and wall separations are two to three times greater at the top than at the bottom. The average tilt of the north and west walls is estimated to be about 0.08. This is comparable to the slope of 0.07 calculated for this section of the sag.

Figure 17 shows the western part of the north interior wall of the crawl space (also figure 15, section D-D'). The ground movements produced two major diagonal cracks in the wall. At floor level, the west crack opened 0.11 ft

FIGURE 17. - North bearing wall of crawl space in house C in 1978 (looking north). The picture shows the change in the nature of separation of the two cracks in the west portion of the wall. Refer to section D-D' in figure 15.

horizontally, and the east crack opened 0.15 ft. Both cracks increased about 0.08 ft in width from bottom to top in response to rigid body tilt. The western crack had a vertical displacement of 0.08 ft that developed as a result of angular distortion. The eastern crack was affected more by horizontal ground movement. This is demonstrated by comparing the ratios of the vertical-to-horizontal crack width (V/H), which is 0.75 for the west crack and 0.28 for the east crack. The west crack also has 0.17 ft of north-south offset at the top.

Figure 15, section C-C', shows that the south bearing wall has undergone displacements similar to the north wall. The crack in the south wall has a low vertical-to-horizontal displacement ratio. Measurements of the vertical crack separation on both the north and south walls are consistent with vertical-ground-displacement contours, which decrease in a southerly and westerly direction.

During subsidence, the eastern portion of the superstructure was supported on bearing walls, but on the west side, the bearing walls settled and moved away from the structure. The ground movements caused the superstructure to be cantilevered out from the east bearing walls. The rigidity of the interior walls helped transfer the loads and allowed the frame to cantilever out over the north and west bearing walls. A vertical separation of 0.6 ft was measured between the north end of the west wall and the superstructure. The loss of support caused severe distortion at the window and door frames, and bending stresses caused tensile cracks and separations.

Because there was no connection between the superstructure and the foundation, the north and west sides of the house were dragged down and moved laterally with the foundation walls. The absence of connections eventually allowed the superstructure to separate from the foundation and to undergo little or no lateral strain in response to the wall extensions because the frictional resistance along the wood-brick interface was negligible.

The northward horizontal ground movement caused the superstructure to move north with respect to southern foundation walls. A horizontal offset of 0.15 ft was measured between the superstructure and the west end of the south bearing wall (fig. 15, sec. B-B').

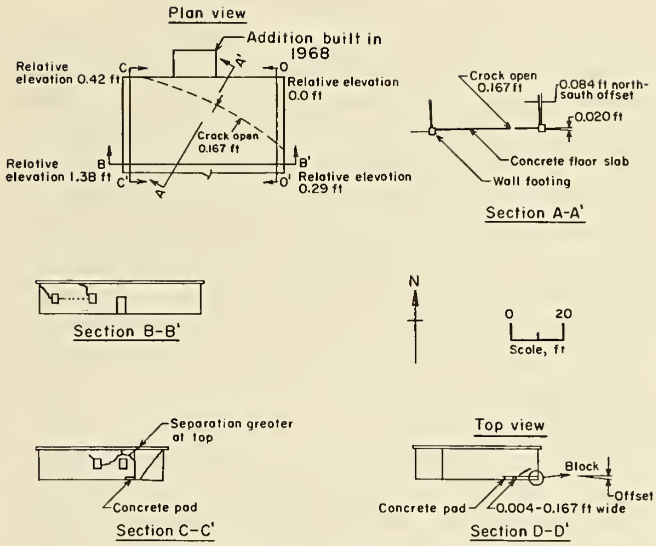

FIGURE 18. - Plan of damage to radio station building. The damage is not inclusive. The relative elevations on the structure were surveyed on July 30, 1967.

BEHAVIOR OF RADIO STATION BUILDING

The radio station building is a masonry-block wall structure founded on wall footings. The floor consists of a wire-mesh-reinforced concrete slab on grade. The building is located in the northeast section of sag 1 where the horizontal ground movements were primarily extensional (figs. 6, 9).

The subsidence profiles indicate that settlement across the building ranged from 0.16 to 1.64 ft. A maximum difference in elevation of 1.38 ft was found from the northeast to the southwest corners of the building. The calculated slope between these two corners is 0.02, which is comparable to sag profile slopes of 0.016 and 0.022 (fig. 8, A-A' and C-C'). The maximum tensile curvature through the building is 2.6×10^{-4} ft^{-1} in a north-south direction and 2.8×10^{-4} ft^{-1} in an east-west direction.

The southwestward horizontal ground movements caused cracking and separation of the foundation and floor slab. A vertical crack in the concrete floor opened 0.167 ft and is oriented subparallel to the vertical-displacement contours (fig. 18, sec. A-A'). The superstructure was displaced horizontally along with the southern part of the foundation. On the north wall, the superstructure failed in shear along the mortar joint just above the foundation and was offset 0.083 ft southward relative to the footing. In addition, the southwest corner of the building was offset by the southwest movement of the foundation. The superstructure appears to have been subjected to angular distortion and tension. The torsional deformation was produced by a change in direction and magnitude of ground movements from south to southwest within the building.

About 80 to 90 pct of the damage occurred within 2 days after the initial movement. The damage included jammed doors and windows, a tilted front wall, and cracks in the floor slab, foundation, and exterior masonry block walls. Several months later, the building was remodeled. This work included a false floor, interior repairs, exterior siding, and a brick facade. A permanent shoring system was also installed to support the south wall.

BEHAVIOR OF RADIO TOWERS

The three radio towers are 200-ft high steel truss structures with pin connections to concrete footings. The footings are 6-ft-square concrete blocks embedded 4 ft in the ground. Four sets of four guy wires oriented orthogonally to one another prevent the towers from swaying excessively and overturning (fig. 2). Ground subsidence structurally damaged all three towers and has caused the guy wires to be replaced and/or retensioned numerous times.

Tower 1 was affected by ground movements associated with the formation of sag 1 in 1967. The southwestern-most guy wire anchor was displaced toward the center of sag 1, which tensioned the guy wire and pulled the top of the tower southwestward. Tower 1 was next affected by formation of sag 2 in 1968: The tower base, which was located near the center of the sag, settled 2.6 ft. In addition, most of the guy wire anchors settled and moved toward the tower base. All of the guy wires had to be tightened three times before the ground movement stopped. Between 1978 and 1981, no additional settlement of the tower has been measured.

The formation of sag 3 affected towers 2 and 3. The eastern part of the sag developed in late 1976. It encompassed the base of tower 2, most of its guy wire anchors, and the southeast set of guy wire anchors for tower 3 (fig. 19). In addition to settlement, the base of tower 2 tilted 0.5 ft and moved northeast. At this time, most of the tower 2 guy wires were loose, and failure of the tower was a major concern. The southeast guy wires of tower 3 tightened as their anchor blocks were pulled southward by the ground movements. Guy wire adjustments were made twice, and new ground transmission wire systems were installed for towers 1 and 2. In early 1978, the guy wires for tower 2 were replaced.

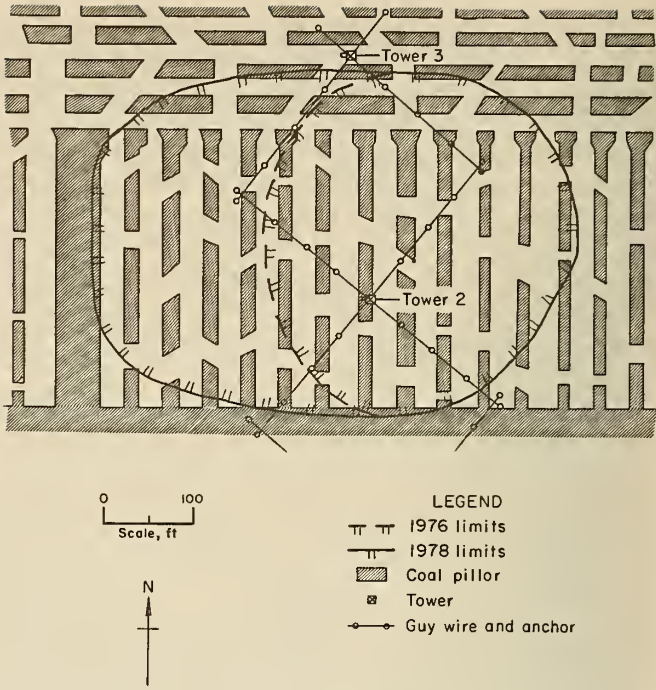

FIGURE 19. - Postulated progression of subsidence associated with sag 3.

In July 1978, additional subsidence occurred, and sag 3 developed in a westerly direction (fig. 19). The renewed subsidence caused additional settlement of the tower 2 base. The cumulative settlement of the tower 2 base is 2.5 ft. The additional movements in sag 3 produced tightening of tower 2 and 3 guy wires. The upper 150 ft of tower 3 was bent as a result of the southwest pull of the guy wire anchor blocks. Guy wires to both towers were retensioned.

Surface waters collected in sags 2 and 3 as a result of subsidence-induced modifications to the surface drainage pattern. The water caused transmitting problems in the ground wire systems. These areas were drained and landscaped in the summer of 1981.

BUILDING RESPONSE TO SAG SUBSIDENCE

The behavior of a structure in response to subsidence depends on the location and orientation of the structure in the subsidence sag, the character of the

ground movements, the structural characteristics and interaction effects, the presence of construction joints, and previous deformation history (12). Subsidence characteristics are usually defined in a two-dimensional profile showing the vertical displacement, slope, and curvature (fig. 20). Compression occurs where the lateral ground displacements decrease in the direction of lateral ground movement, whereas extension exists where ground displacements increase in the direction of lateral movement.

Sags develop differently over room-and-pillar mines in Illinois than over modern high-extraction operations. The movement of a longwall face or pillar extraction line produces a traveling (dynamic) wave on the surface, which subjects a structure first to tension, then compression. However, in older, low-extraction mines, subsidence sags develop over a limited area governed by the mining and geological conditions of the site and the instability of the roof-pillar-floor system. Consequently, most sags in Illinois are caused by pillar crushing and/or settlement into the mine floor (14). Thus a surface structure undergoes deformations defined by its position on the sag. In some cases, structures are subjected to several cycles of deformation caused by overlapping sags that develop in an area. In general, when subsidence occurs in a residential area, most of the structures are located in the tension zone because its area is much larger than that of the compression zone (12).

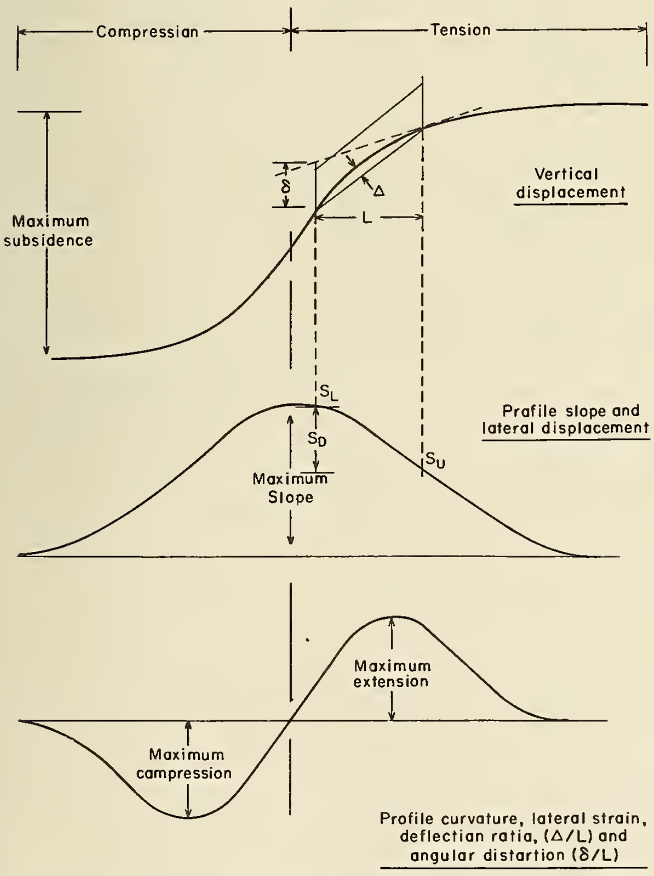

FIGURE 20. - Relationships between subsidence profile characteristics and ground deformations.

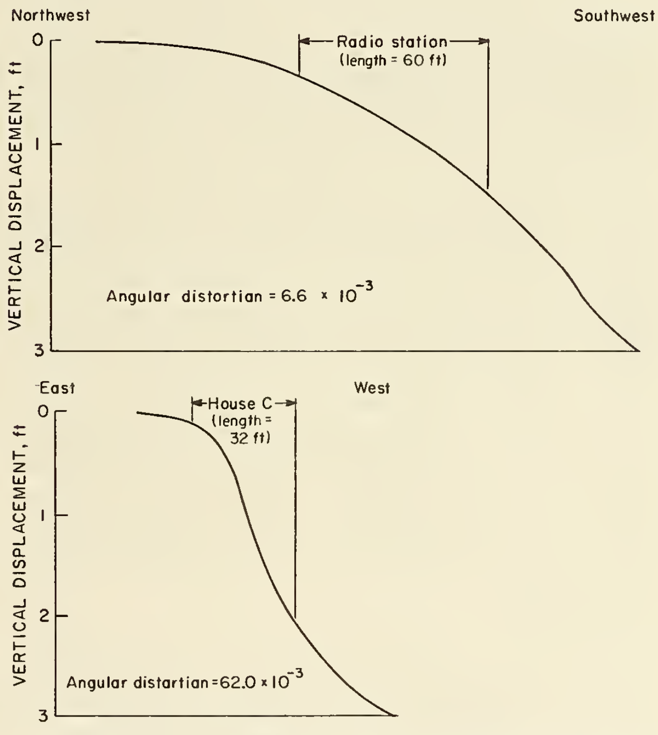

FIGURE 21. - Comparison of subsidence profiles of radio station building and house C. No horizontal scale is indicated because no common origin exists for both structures. However, the length of each structure is given so that a comparison can be made regarding vertical displacement over the length of each structure.

The nature and intensity of structural deformations usually change along the length of the structure because of variations in the ground surface displacements. The induced deformations and rigid body movements can be estimated by parameters that described the subsidence profile along the length of the structure. The profile parameters include the slopes at the lower (S_L) and upper (S_U) ends of the structure, the difference between the lower and upper slopes (S_D), the angular distortion, the deflection ratio, and the curvature (fig. 20).

Lateral ground displacement has the same pattern and is proportional to the profile slope. The magnitude of lateral strain along a section of profile can be related to the section curvature, which is estimated by dividing the difference in slope (S_D) at the ends of the section by the length (L) of the structure. The section curvature is also proportional to the deflection ratio which is used to estimate the bending deformation (fig. 20).

Angular distortion is used to estimate the induced vertical shear strains. It is calculated as the vertical distance between the profile tangent at the lower and upper ends of the structure along the subsidence profile (δ) divided by the length (L) of the structure (fig. 20). Rigid body rotations are not included in the angular distortion parameter. The induced tilt is a function of the profile slope. Induced rigid body horizontal and vertical displacements across the structure are related to the differences in lateral displacement and differential settlement.

The radio station building and house C were located in the tension zone of the same sag. A comparison of the subsidence profiles along both structures taken parallel to the direction of horizontal ground movement is shown in figure 21. The subsidence profile along house C is much more severe than the profile along the radio station building. For example, the angular distortion along the house is 62.0×10^{-3} compared with 6.6×10^{-3} along the radio station building. Other profile parameters (table 2) also show that house C was subjected to more severe ground movements.

Boscardin (32) has established damage criteria for masonry bearing wall structures in terms of angular distortion and horizontal strain. Using his criteria and assuming only angular distortion, both structures fall into a "severe to very severe damage" category because both structures exhibit angular distortions of 6.6×10^{-3} or greater. Damage to both structures is also severe under visible damage and cost of repair criteria developed by Burland, Broms, and de Mello (17). Their classification system is given in table 3.

The radio towers were subjected to a number of different subsidence events and sag interactions. The base of tower 2 was tilted during both subsidences of sag 2, and distortion occurred in all three towers as a result of tightening of the guy wires. Tightening occurred primarily when there was relatively little or no settlement of the tower bases. No established damage criteria for the response of these structures to ground movements were found in the literature.

TABLE 2. - Summary of building damage and associated ground movements

	Radio station building[1]	House C[2]
Slope, lower end of structure (S_L)...pct..	2.56	8.50
Slope, upper end of structure (S_U)...pct..	1.18	0.30
Slope difference (S_d) = S_L - S_U......pct..	1.38	8.20
Angular distortion........................	6.6×10^{-3}	62.0×10^{-3}
Curvature.........................ft^{-1}..	2.3×10^{-4}	3.0×10^{-4}

[1]Foundation consisted of wall footings; superstructure was made of concrete block, 1 story high.

[2]Foundation was brick basement walls and footings; superstructure was wood frame with exterior siding 2 stories high.

TABLE 3. - Classification of visible damage to walls, with particular reference to ease of repair

Degree of damage	Approx. crack width,[2] mm	Description of typical damage[1] (with ease of repair underlined)
Negligible...	<0.1	Hairline cracks.
Very slight..	<1	Fine cracks that can be treated easily during normal decoration. Perhaps isolated slight fracture in building. Cracks in external brickwork visible upon close inspection.
Slight.......	<5	Cracks easily filled. Redecoration probably required. Several slight fractures showing inside of building. Cracks are visible externally, and some repointing may be required externally to ensure weathertightness. Doors and windows may stick slightly.
Moderate.....	5-15	Cracks require some opening up and can be patched by a mason. Recurrent cracks can be masked by suitable linings. Repointing of external brickwork and possibly a small amount of brickwork to be replaced. Doors and windows sticking. Service pipes may fracture. Weathertightness often impaired.
Severe.......	15-25	Extensive repair work involving breaking out and replacing sections of walls, especially over doors and windows. Windows and door frames distorted, floor sloping noticeably. Walls learning or bulging noticeably; some loss of bearing in beams. Service pipes disrupted.
Very severe..	>25	Requires major repair involving partial or complete reconstruction of building. Beams lose bearing; walls lean badly and require shoring. Windows broken from distortion. Danger of instability.

[1]In assessing the degree of damage, account must be taken of its location in the building or structure.

[2]Crack width is only one aspect of damage and should not be used on its own as a direct measure of damage.

Source: Burland, Broms, and de Mello (17).

SUMMARY

To augment the characterization of mine subsidence over room-and-pillar mines in Illinois, the Bureau of Mines and the University of Illinois initiated an investigation and evaluation of mine subsidence at Hegeler, IL. Detailed descriptions of the surface subsidence and the effects of the subsidence on structures at the site have been presented.

The site, in east-central Illinois, is covered with 29 to 47 ft of glacial till above 90 to 105 ft of bedrock. The mined Herrin (No. 6) coal is found 130 to 135 ft below the surface and ranges from 6.1 to 6.4 ft thick. The roof rock is composed of the Energy Shale that varies in thickness from 29 to 35 ft. The Herrin (No. 6) coal was mined using a modified room-and-pillar method with extraction averaging 70 pct. The coal beneath the study site was mined from about 1960 to 1967.

Mine collapse caused three subsidence sags to form at the site. Sag 1 occurred in July 1967, sag 2 in May-June 1968, and sag 3 in November-December 1976. The mine failures causing the sags to form probably were initiated by pillar crushing or perimeter bearing failure of the pillars into the floor.

Subsidence sags 1 and 2 each formed as one major event, whereas sag 3 formed in two events, which occurred in 1976 and 1978. The main subsidence movements for each sag took place within 2 months. The average diameter of the subsidence sags range from 280 to 430 ft with maximum settlements of 3.0 to 3.5 ft. When the sags are compared with other sags reported over room-and-pillar mines in Illinois, they show more severe subsidence profile characteristics even though the other mines have comparable subsidence factors and similar depths.

Sag 1 severely damaged three houses and a radio station, broke numerous utility lines, and tensioned a guy wire to a transmitting tower. The radio station was subsequently repaired and remodeled; however, two of the houses were abandoned and removed in 1975, and the third house was removed in 1978. The maximum slope across the radio station building was 0.022 and the curvature was 2.3×10^{-4} ft^{-1}. The most severe profile characteristics were measured across house C where the slope was 0.07 and the curvature was 3.0×10^{-4} ft^{-1}. Angular distortions of 6.6×10^{-3} and 62.0×10^{-3} were calculated along the radio station building and house C, respectively. In two damage classifications, both structures were severely to very severely damaged.

Sags 2 and 3 affected the three radio transmitting towers. The bases of towers 1 and 2 settled 2.6 and 2.5 ft, respectively. The third tower base was not affected. The subsidence movements caused tensioning and loosening of the guy wires. Furthermore, the movements and drainage problems made the radial ground wire transmission systems ineffective. New ground wire transmission systems for towers 1 and 2 were installed, guy wires were replaced, and the areas around the base of the towers were drained and regraded to prevent further water damage. The radio towers have been structurally damaged, primarily by bending and distortion from guy wire forces that were transmitted to the towers by ground movements that occurred outside the tower base.

The observations and data obtained at the Hegeler site are instructive for characterizing the types of ground movement and structural damage that may occur over unstable room-and-pillar mines. Although precise presubsidence elevations were not known, sufficient information was available to confidently determine those conditions. Our understanding of subsidence and its effects on the ground surface and structures is limited because of the lack of available data. Observation, collection, and interpretation of data will help us understand what to expect when subsidence occurs and how best to respond to minimize its effects.

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APPENDIX.--CHRONOLOGICAL LIST OF EVENTS RELATED TO SUBSIDENCE AT HEGELER, IL

Date and time	Damage
	SUBSIDENCE SAG 1
7/21/67:	Radio station damaged as follows:
12:00 noon....	Doors began to stick.
2:00 p.m.....	Large cracks developed in structure.
2:30 p.m.....	Off the air for about 45 min.
11:30 p.m.....	Off the air; noticed additional damage.
7/21/67: Afternoon to 12 midnight.	Other damage as follows: 0.17- to 0.25-ft-wide crack developed in pavement. At least 3 gas service lines broken; telephone lines pulled away from houses.
7/22/67: 7:30 a.m. to 12 midnight.	Radio station damaged as follows: Back on the air. New cracks formed and existing cracks opened. Southwest guy wire to tower 1 was significantly tensioned.
	Other damage as follows: 3 houses underwent additional serious damage due to subsidence; cracks in basements, separation of superstructure and foundation, distortion of superstructures, and utility damage. News accounts reported maximum settlement at about 4.0 ft.
7/23/67.........	80 to 90 pct of damage to radio station building had occurred.
10/67...........	Remodeling of radio station building began (movements appeared to have stopped).
5/69 or 6/69....	Separation and cracking of new addition to structure and to remodeled radio station building.
	SUBSIDENCE SAG 2
5/68 or 6/68....	Radio station damaged as follows: Tower 1 settled 1.5 to 2.0 ft in 3 to 4 weeks, and 2.75 ft in 6 weeks. Guy wires retensioned 3 times. Surface drainage noticeably affected.
5/69 or 6/69....	Water ponded around base of tower 1.
	SUBSIDENCE SAG 3
11/76 or 12/76..	Tower 2 of radio station settled about 3 ft. Guy wires were retightened. Near failure of tower 2 (foundation tilted 0.5 ft to the east).
2/78 or 3/78....	Water ponded around base of tower 2 of radio station.
7/78............	Ground anchor of southwest guy wires on tower 3 settled. Top of tower bent.
6/25/79.........	Tower 2 settled an additional 0.08 ft between 10/78 and this date.

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